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The SALT PROBLEM in IRRIGATION AGRICULTURE

Research at the United States Regional Salinity Laboratory

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FOREWORD

A number of important agricultural problems are primarily regional in scope, as distinguished from others that are limited to individual States and still others that are of country-wide interest. To meet the need for research on such problems, the Bankhead-Jones Act of 1935 provided for regional laboratories, to be administered by the Secretary of Agriculture, which would mobilize scientific resources for a fundamental attack on some of the most important of these problems.

Nine such laboratories have been established. Each deals with a problem or group of problems selected in cooperation with the State agricultural experiment stations of the region as being among the most important faced by agriculture in that section of the country. The States cooperate with the Department in planning and carrying out the research program of each laboratory on a regional basis. At the same time the subjects under investigation are of importance to all major agricultural regions, and the results obtained by the laboratories contribute to agriculture on the national and local, as well as the regional level.

This publication is one of a series, each of which describes the work of one of the Bankhead-Jones laboratories, covering the complete program, the results obtained to date, and the continuing research. Papers on various phases of the work have been published by all the laboratories as Department publications and in technical journals.

The laboratories and their locations are as follows:

U. S. Regional Vegetable Breeding Laboratory, Charleston, S. C.
U. S. Regional Pasture Research Laboratory, State College, Pa.
U. S. Regional Soybean Laboratory, Urbana, Ill.
U. S. Regional Swine Breeding Laboratory, Ames, Iowa
U. S. Western Sheep Breeding Laboratory, Dubois, Idaho
U. S. Regional Animal Disease Research Laboratory, Auburn, Ala.
U. S. Regional Poultry Research Laboratory, East Lansing, Mich.
U. S. Regional Salinity Laboratory, Riverside, Calif.
U. S. Plant, Soil, and Nutrition Laboratory, Ithaca, N. Y.

P. V. Cardon,
Administrator of Agricultural Research.

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THE SALT PROBLEM IN IRRIGATION AGRICULTURE

Research at the United States Regional Salinity Laboratory [1]

SALINITY A PRIMARY PROBLEM IN IRRIGATION AGRICULTURE

The continued prosperity of the entire West is directly dependent on its irrigated lands. Although the irrigated areas (fig. 1), present or potential, constitute only a small fraction of the western half of the United States, they are the heart of western agriculture. They lie along river channels and are adjacent to areas where the rainfall, though low, is sufficient for dry farming and the maintenance of pasture for livestock.

Above these arable lands lie extensive areas of rough and mountainous land in pastures and forests. In many localities, the aggregate value of the products of the dry farms, the pastures, the forests, the mines, and local manufacturing industries greatly exceeds the value of the products of irrigated land. But if irrigation agriculture should fail, these other enterprises would be jeopardized. Concern for the future of our irrigated land, therefore, is not limited to the few who live on that land but is shared by the whole population.

In areas where irrigation agriculture is practiced the economic importance of the salt problem is generally recognized, but many practical problems are still unanswered. Although the soils of some irrigated areas are nonsaline and are in little danger from salt injury the accumulation of salt is a continuing hazard to crop production on much of the 20 million acres of irrigated land in the Western States.

Losses from reduction in yield and quality of crops may occur on lands containing some salts but not enough to throw them out of production. It has been estimated that in many cases such losses amount to 10 to 25 percent of the yield.

It is to be expected that the salt danger will increase rather than diminish, since the trend in irrigation agriculture is in the direction of utilizing all the available water, including the drainage water and return flow from older irrigated lands. Loss of drainage water from irrigated areas upstream and the pick-up of saline ground water by the main stream result in more salt downstream. The downstream waters are therefore less desirable for use in irrigation.

The maintenance of successful agriculture in areas now under irrigation requires more exact and detailed information regarding the chemical and physical properties of western soils, about irrigation waters and the salts contained in them, and on the effect of the salts on the soils and on plants.

[1] This publication was prepared at the U. S. Regional Salinity Laboratory by H. E. Hayward, director, and O. C. Magistad, former director, with the assistance of the staff. Acknowledgment is also made to Gordon W. McBride, formerly of the Office of the Administrator, Agricultural Research Administration; Carl S. Scofield, formerly of the Bureau of Plant Industry, Soils, and Agricultural Engineering; F. W. Parker and Byron T. Shaw, of the same bureau; and to the directors of the agricultural experiment stations of the 11 Western States and Hawaii.

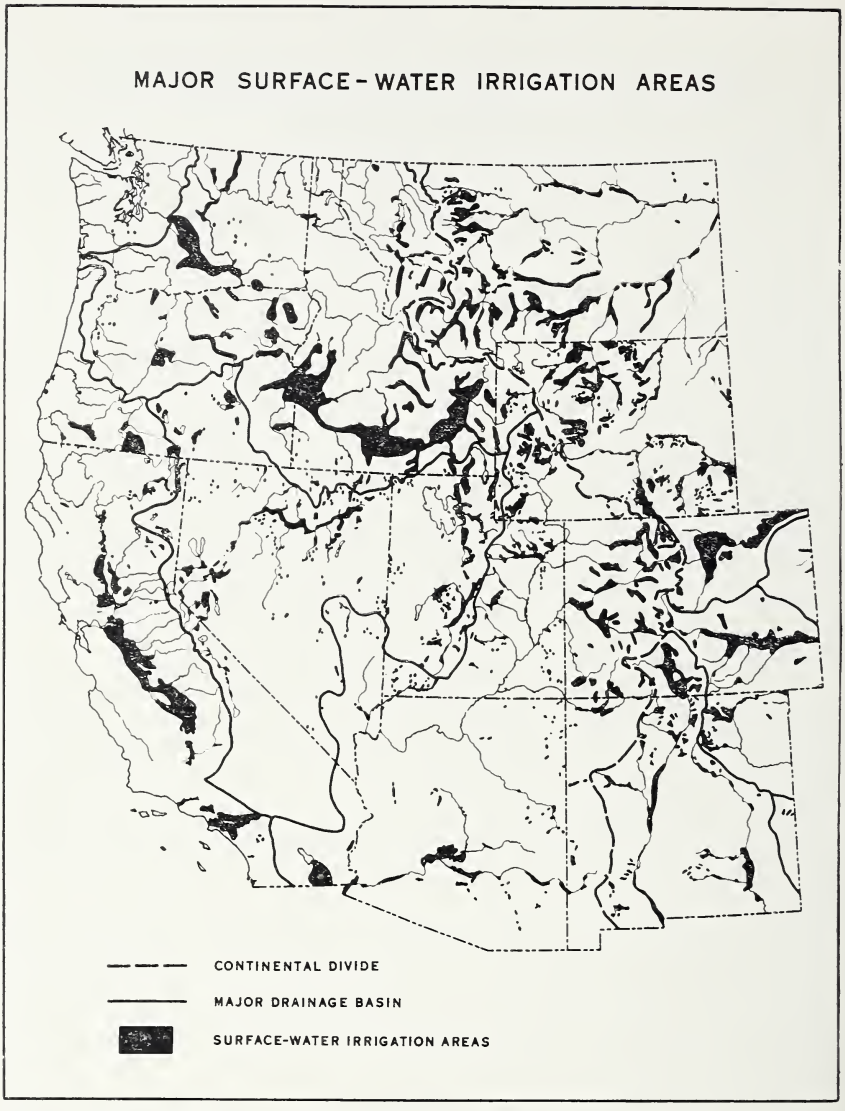

FIGURE 1.—The wide extent of irrigation in the Western States is shown on this map. Salinity problems are actual or potential in practically all of the solid black areas. (Map prepared by Bureau of Agricultural Economics.)

The extension of irrigated areas through reclamation will intensify the use of our water resources. In this connection it is important that dependable forecasts be made of the response of soils to irrigation and reclamation practices. Surveys in which the knowledge of soil, water, and plant relationships under saline conditions is applied should aid materially in land appraisal and prevent waste and failure in the development of new reclamation projects.

THE SALT PROBLEM IS REGIONAL

Irrigation areas and problems rarely if ever follow State lines. Broadly speaking, there are 10 major irrigation areas in the Western States. Each of these areas includes parts of more than one State, and many of the problems are common to all areas. Because of this and the fact that salt problems are general in the irrigated region, studies of salinity can be most effectively organized on a regional basis. The basic findings resulting from such regional studies may also be applied to many local situations in the several States within the region without duplication of manpower and research facilities.

THE SOURCE AND ACCUMULATION OF SALTS

In arid and semiarid areas in the Western States soluble salts tend to accumulate in the soil in amounts harmful to crop production. The salts are derived primarily from the soil and rocks through which percolate the waters that supply the water table and the irrigation streams. The salt in rocks and soil may have accumulated when the area was a portion of the ocean floor or the bottom of a salty lake. The chemical breakdown of minerals has also contributed to the salt supply. In regions with sufficient rainfall, these salts are leached from the soil and carried away in streams or moved downward to depths below the root zone, so that they do not constitute a problem in agriculture. But in sections of limited rainfall where irrigation is required for crop production the salts are not leached out, and the experience of the past century has shown that crop failures are often caused by the accumulation of soluble salts in the surface soil. Thus the problem of soil salinity is primarily one of irrigated lands, and it is likely to become more serious with the more complete use of our water resources.

Salts continue to accumulate in soils of irrigated areas where greater quantities are brought in than are removed. The irrigation waters of the West contain from one-tenth of a ton to possibly 5 tons of salt per acre-foot of water. While some irrigated areas use only 2 feet of water (24 inches of irrigation in addition to a few inches of rainfall), others, where the summers are long and hot, use up to 5 feet of water or more a year. On an acre of land, therefore, irrigation water may add as much as 1 to 10 or more tons of salt each year. Some salt may be taken up by the crop and removed with it, and some dries on the surface of the soil and blows away, but the amount of salt thus lost is small compared with the quantities added.

The only effective method for the removal of salt from soil is by means of water which passes through the root zone of the soil, but if the amount carried away is less than the quantity brought in by irrigation water, salt will accumulate. Frequently farmers are not aware that to prevent salt accumulation and consequent decrease in crop yields they must remove as much salt as is brought in. In some areas an effort is made to stretch the supply of irrigation water over too many acres, with the result that the soil is not wetted below a depth of a few feet. In other areas, the ground-water table is so close to the surface as to hinder the removal of the salt from the root zone. When a high water table exists, the upward movement of saline ground water results in a continuing accumulation of salt in the surface soil.

THE REGIONAL SALINITY LABORATORY AND ITS OBJECTIVES

In 1937, a conference of the directors of the agricultural experiment stations of the 11 Western States and Hawaii and representatives of the United States Department of Agriculture was held to discuss regional agricultural problems. It was agreed unanimously that salinity was a major problem in irrigation agriculture, and the recommendation was made that the Federal Government establish a "regional research laboratory for investigations of the relationships of the salinity of irrigation waters, and of soil conditions, to plant growth and related factors involved in a permanently successful irrigated agriculture."

The following objectives were outlined to serve as a guide in developing the research program:

1. To study the reactions of crop plants and the soil to the several naturally occurring salts at various concentrations in both artificial and natural solutions.
2. To investigate the salt tolerance of crop plants to various salt concentrations as expressed in changes in form and structure or other symptoms.
3. To determine the amount of water that should be applied to soils to avoid harmful salt concentrations.
4. To study the trend of salinity conditions in the several areas where such problems exist (fig. 2).
5. To explore the possibilities and limitations of adequate and efficient drains in order that necessary reclamation practices may be adopted.
6. To develop practical applications of the laboratory findings so that the reactions of crop plants can be predicted when field conditions are known and controlled.

At the initial conference and in all subsequent ones, cooperation between the State agricultural experiment stations and the laboratory was emphasized. It was pointed out that the function of the laboratory was not to replace or duplicate work being done by the States but that its program was to supplement and be integrated with such work. The Secretary of Agriculture approved the establishment of the laboratory as a research project under the Bankhead-Jones Act in 1937, and work was begun early in 1938.

Location, Facilities, and Personnel

The Salinity Laboratory is located at Riverside, Calif., 50 miles east of Los Angeles. This site was chosen by representatives of the State agricultural experiment stations for several reasons. Most of the crops of the West can be grown at Riverside in either summer or winter, and the effect of climate can be studied by conducting tests in the nearby coastal region and in the adjacent desert region to the east. The excellent library facilities of the Citrus Experiment Station of the University of California at Riverside make it unnecessary to use laboratory funds for establishing a library. Low operating costs resulting from the mild climate, and the proximity of a large industrial city where scientific equipment and supplies may be obtained are other important considerations.

The buildings of the Salinity Laboratory are situated at the foot of Mount Rubidoux, about a mile west of the business section of Riverside. Offices and laboratories occupy a small two-story building, connected with which are two large greenhouses with equipment for carrying out indoor experi-

ments. Nearby are two installations of large-scale outdoor sand beds, one set being large enough to grow orchard trees to maturity. In the rear are service buildings containing a machine shop and a carpenter shop where research equipment is built, soil and plant preparation rooms, supply rooms, and an analytical laboratory. The scientific staff consists of about 20 people selected for their special training in the fields of science that relate to the problem of salinity. They are botanists, chemists, engineers, plant physiologists, physicists, soil scientists, and scientific aides.

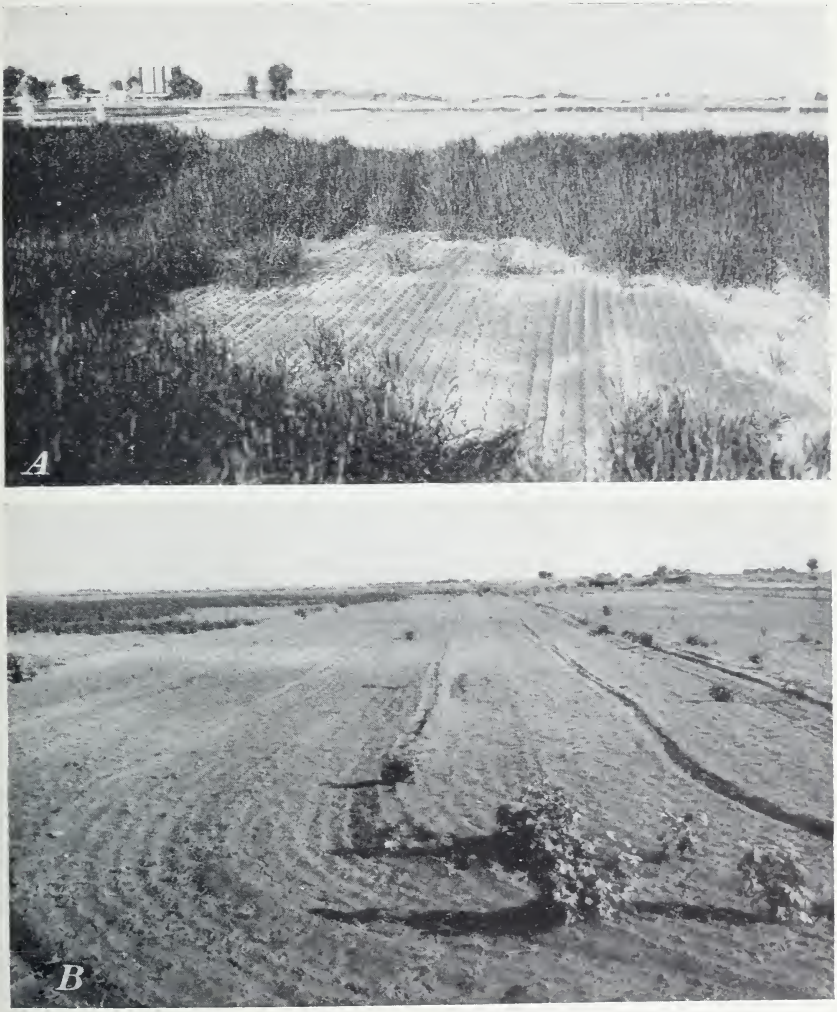

FIGURE 2.—The effects of salinity are sometimes very striking. *A*, A thriving barley crop abruptly stopped by a "salt spot"; *B*, the result of planting cotton on sandy loam with inadequate subsoil drainage and excessive salinity. In many cases the salt is more uniformly distributed than in the fields shown, with no sharp line of demarcation between good plants and no plants. If the farmer has no point of reference, his entire crop, though actually stunted by excessive salt, may appear to him to be "normal."

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The administrative supervision of the Salinity Laboratory was originally placed under the Division of Fruit and Vegetable Crops and Diseases of the Bureau of Plant Industry, Soils, and Agricultural Engineering. In July 1945, it was transferred to the Division of Soils, Fertilizers, and Irrigation of the same bureau. This change was made to bring about a more effective coordination of the entire research program in soils and irrigation including those phases related to salinity.

COOPERATION WITH STATE EXPERIMENT STATIONS AND OTHER AGENCIES

Close cooperation is maintained with the State agricultural experiment stations in the region by means of periodic conferences which have been held at Riverside each year except during the war. In the future, occasional meetings may be held elsewhere in the region, so that salinity problems such as those related to drainage and irrigation may be discussed and observed in the field. At these conferences each of the cooperating States is represented by a "research collaborator" from the staff of the agricultural experiment station who is familiar with the research program of the laboratory as well as with the related work in his own State. The current work is reviewed, recent accomplishments are discussed, and the future research program is considered. In this way the work of each agricultural experiment station dealing with the salinity problems in that State is coordinated with the program of the regional laboratory so that the two programs supplement rather than duplicate each other. Through this joint effort the research group in each State contributes to the solution of regional problems.

In addition to its work with the States, the Salinity Laboratory cooperates with other agencies whenever its personnel and facilities can render service in helping solve the salt problems of western agriculture. At the present time cooperative work is being carried on with the Soil Conservation Service, Bureau of Reclamation, Indian Service, and several irrigation and drainage districts. The staff of the Salinity Laboratory is not large and cannot carry on extensive investigations in the field. But, through cooperation with other agencies engaged in such work, technical assistance can be exchanged for the opportunity to apply the results of the basic research carried on at the laboratory.

WHAT HAS BEEN LEARNED

The salt problem is complex because it involves the soil in which the plant grows, the water and soluble nutrients of the soil solution used by the plant, and the plant itself. In the final analysis, the behavior of the plant is the best index of its environment (soil, water, climate), and "indicator" plants play an important role in the evaluation of saline conditions. But to extend our knowledge of the factors involved in the salt problem it is necessary to study them separately and then investigate their interrelationships. To do this, the research program of the Salinity Laboratory includes three broad fields of investigation: (1) Studies of the chemical and physical properties of saline and alkali soils, (2) studies of saline waters and soil-water relationships, and (3) studies of plant responses to saline and alkali conditions. Representative work that has been done in these fields by the laboratory and other agricultural research agencies is described in the following sections.

Salty Soils and Their Improvement

The kind of soil most desirable for irrigation farming is a fine sandy loam that drains well. A desirable water for irrigation should have a low total salt content and a low percentage of sodium. In western agriculture such a favorable combination is not always possible. The water available must be used, and though there is more latitude in the choice of land, this is also restricted. The soils program of the Salinity Laboratory includes detailed studies of representative soils from saline areas throughout the West. Approximately 950 soil samples have been collected for special study, and soil records are available which serve as a valuable source of information in appraising salinity conditions in western soils.

Saline and Alkali Soils

Salty soils differ among themselves in many respects and no two are exactly alike. Hilgard, an early American investigator of western soils, classified salty soils as "black alkali" or "white alkali." The "black alkali" soils were so named because, when they dry, a brown or black crust may be left on the surface owing to reactions by which organic matter is dissolved. This does not occur, however, when arid soils are very low in organic matter. Today we recognize that "black alkali" soils contain a very large proportion of sodium which is adsorbed on the surfaces of the small clay particles. These soils have a pronounced alkaline reaction, especially when the salt content is low. "White alkali" soils correspond with those now referred to as saline soils and were so called because the salts frequently accumulate on the surface, giving the soil a white appearance. In them calcium and magnesium salts predominate, the soil contains little adsorbed sodium, and organic matter does not dissolve.

It is important to distinguish between saline ("white alkali") and alkali ("black alkali") soils because the former usually have good structure, take water well, and drain well, while the latter run together or "puddle," have poor structure, take water very slowly, and are difficult to leach. A saline soil may be made productive by leaching out the salt, but the alkali soil must be changed chemically by replacing the excessive sodium held by the soil with calcium and then leaching out the replaced sodium salts.

The Effect of High Sodium Content in Soils

It is the harmful effect of sodium on the structure of the soil that makes it undesirable to use irrigation water containing a high percentage of sodium. Where the sodium percentage of the irrigation water is very high, the soil retains much of this sodium and develops the characteristics of an alkali soil. It becomes waterlogged, little air penetrates the root zone, and plant growth is reduced, mainly because of poor physical condition.

The effects of different proportions of sodium salts on a number of soil types commonly found in the irrigated areas have been studied. Portions of the soils were first leached with waters containing several different percentages of sodium salts. They were then leached with water having a low salt content, and the permeability was measured by observing the rate at which the water passed through the soils. In Hanford soil, which occurs in large areas in the West, the rate of water intake decreased from about 2 inches per hour to less than 1 inch per hour after being leached with a

90-percent sodium water. With Altamont soil, a coastal soil that is slightly acid and relatively high in organic matter, the permeability following the same treatment decreased from about 4 inches per hour to practically zero. The results indicate that irrigation with a water containing a high percentage of sodium usually leads to a decrease in permeability, and other work has shown that reclamation must involve physical as well as chemical changes. It is important that soil be allowed to dry following reclamation treatments in order for favorable physical changes to take place to any appreciable extent.

The laboratory has investigated the effect of sodium nitrate and ammonium fertilizers on the permeability of 51 soils representative of the irrigated regions of the West. The water applied to the soils was of the same chemical composition as the irrigation water used in the field. When sodium nitrate was added to the soil in concentrations such as are applied in band fertilization of truck crops, the rates of water penetration were reduced by an average of 41 percent, in some cases as much as 86 percent. The reduction was serious in about half the soils. It was found that the same amount of sodium nitrate applied in the irrigation water in small increments had little effect on soil permeability, and it has been suggested that this fertilizer be applied in such a way that its concentration in the soil solution is kept very low. Ammonium nitrate and ammonium sulfate in high concentrations tested under laboratory conditions tend to decrease permeability, but to a lesser degree than sodium nitrate. Other studies have been made on the effect of organic matter, gypsum, and drying on soil permeability and the rate of entry of water into soils irrigated with high-sodium waters.

The Importance of Good Drainage

Where irrigation has been practiced for a long time, there is usually a problem of removing soluble salts that have accumulated or of restoring alkali lands to production. In both cases good drainage is absolutely essential.

Good drainage implies (1) a relatively permeable soil through which water moves readily, and (2) the absence of a water table within a depth where it would greatly influence the water retained in the root zone. Some soils are so impermeable that water will evaporate from the surface faster than it will enter the soil. Such soils could not be considered as having good drainage. Sometimes, however, soils of low permeability can be improved by proper management. With alkali soils improvement may consist in chemical treatments to convert the soils to normal calcium soils, coupled with physical changes induced by alternate freezing and thawing or wetting and drying.

The permeability of the soil can be studied in the field, but it is often more convenient to make such studies in the laboratory with cores of undisturbed soil obtained from locations in the field for which data are desired. The Salinity Laboratory has developed an apparatus by which cores can be cut in an hour or two (fig. 3).

The cores are set up in the laboratory in such a way that water of known characteristics can be supplied and the rate at which this water passes through each core can be measured (fig.4).

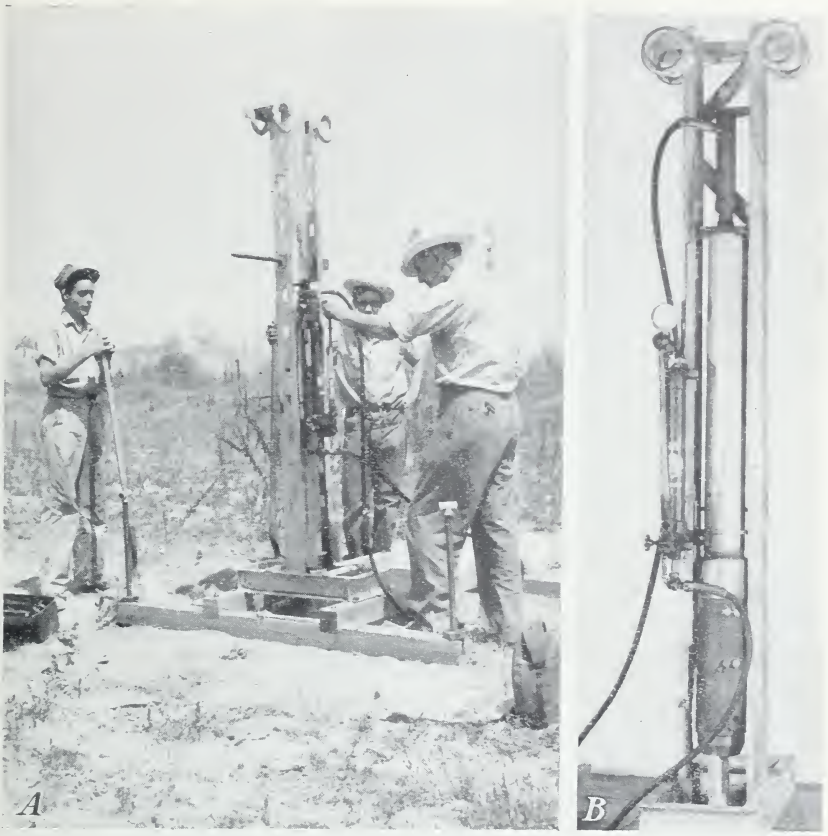

FIGURE 3.—*A*, To obtain a soil core in the field, a hydraulic jack forces a sampling tube into the ground at the point selected. Friction is reduced by hand excavation around the tube as it is pushed down. Screw type anchors at each corner of a broad frame hold the derrick in position while the sample is obtained. *B*, A close-up of the soil-core derrick shows the hydraulic pump which forces the cutter into the ground. In this picture the cutter rests on a piece of wood so it can be photographed; in operation it would be at or below the surface of the soil.

The effect of chemical treatments on permeability can be determined by using disturbed soil samples in a permeability apparatus (fig. 5). For example, the effect of additions of gypsum or other treatments on permeability can be studied by this method.

Either artificial or natural drainage requires (1) a permeable soil, and (2) the natural or artificial removal of ground water at a rate that will maintain the water table at an adequate depth. Under most conditions the water table should be at least 6 to 10 feet below the surface, but where salinity is low a water table nearer the surface may not be harmful. Where artificial drainage is required, the system consists of two parts—a means for collection of ground water, and a disposal system. Three methods of artificial drainage are used—tile systems, open drains, and pumped wells.

Where the permeable surface soil is underlain with gravel deposits in which wells of satisfactory capacity can be developed, pumping from wells may be the most feasible and economical method of drainage. In many irrigation projects, drainage is accomplished by means of deep open drains, with tile drains frequently used as an adjunct to them.

The water collected is usually removed by means of large outlet drains which discharge back into the river system. Sometimes, in relatively flat areas, as in the Sacramento Valley in California, it is necessary to pump the water back into the river. In many places where drainage is achieved by pumping from wells the water is of such quality that it can be reused for irrigation, either directly or after being mixed with water of lower salt content.

The Salinity Laboratory has perfected small, cheap, but efficient observation wells by which the depth to the water table can be determined and observed throughout the year. By having these wells terminate at different depths, the pressure and direction of movement of ground water can be determined. By their use the engineer can obtain information about underground water conditions that will help him in planning drainage systems. Under artesian conditions when there is sufficient ground-water pressure to force water to the soil surface, drainage is very difficult. In this case, it will be necessary to reduce the pressure of the underground water by pumping or other means.

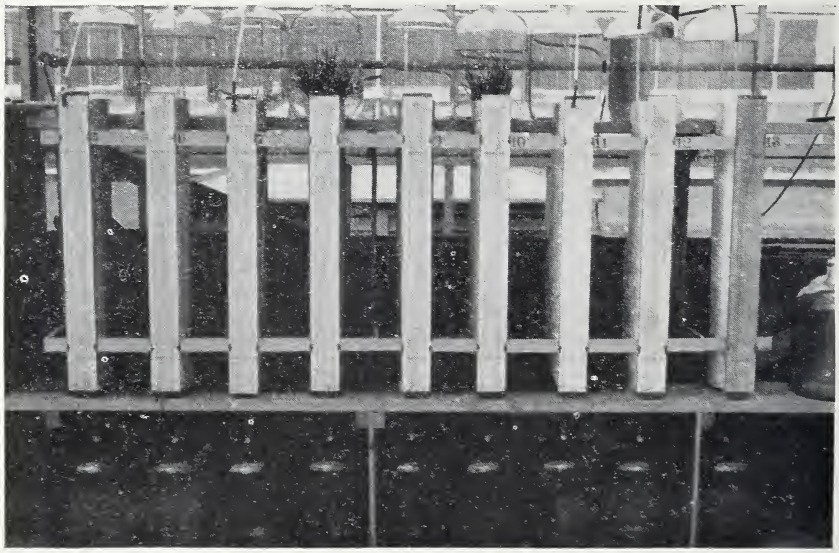

FIGURE 4.—Several soil cores are mounted in the laboratory for permeability tests. The readings from manometers on the sides of the cores indicate the relative permeability at different levels in each core. The grasses growing in some of the cores can be used periodically to promote natural conditions of water removal from the soil by transpiration from the plants. During permeability measurements water is kept standing at a constant level on the surface of all the cores, and the rate of discharge of water at the bottom is measured.

FIGURE 5.—Permeability tests on a number of soil samples can be run at one time with this equipment. Waters of known salt concentration are run over the surface of the soil columns and the water that passes through the soil is collected in graduated cylinders and measured at regular intervals. In this way the rate of movement of water through the soil and the effect of various salts on that rate can be determined.

How Alkali Soils Can Be Reclaimed

Alkali soils contain an excessive amount of sodium which is held by the finer soil particles. Because of this, alkali soils usually have a poor physical condition, and in addition plants growing on them may be affected by nutritional deficiencies. To reclaim such soils they must be changed chemically and improved physically.

The chemical changes consist in exchanging calcium for sodium and then leaching away the sodium salts. Any soluble calcium compound will do, and the greater the concentration of calcium in the water used for reclamation, or in the soil solution bathing the soil particles during reclamation, the more rapidly this process will take place. Small amounts of calcium dissolved from lime (calcium carbonate) contained in some soils will, in time, cause the desirable chemical changes. If the soil contains gypsum (calcium sulfate), chemical reclamation will progress more rapidly. If the soil does not contain it, gypsum can be added on the surface where it can be dissolved by the irrigation water. Other soluble calcium compounds such as calcium chloride are also very helpful but are usually too expensive.

Studies of a number of alkali soils have been made at the laboratory using pot tests to diagnose the soil condition and to determine the effect of

chemical treatments. On the basis of such tests recommendations can be made for field studies. Many saline and alkali soils are low in available phosphorus and will give better crop yields if phosphate fertilizers are used. Superphosphate, treble superphosphate, and ammonium phosphate are among those generally recommended. Results of experiments of this type are illustrated in figure 6.

During reclamation many farmers find it helpful to apply several tons of gypsum per acre, flood the land inside of levees for a week or more, dry out the soil in the basins, and then flood again. Alternate flooding and drying are repeated until weeds and grass grow well and the permeability is improved. Growth of vegetation, even weeds, should be fostered be-

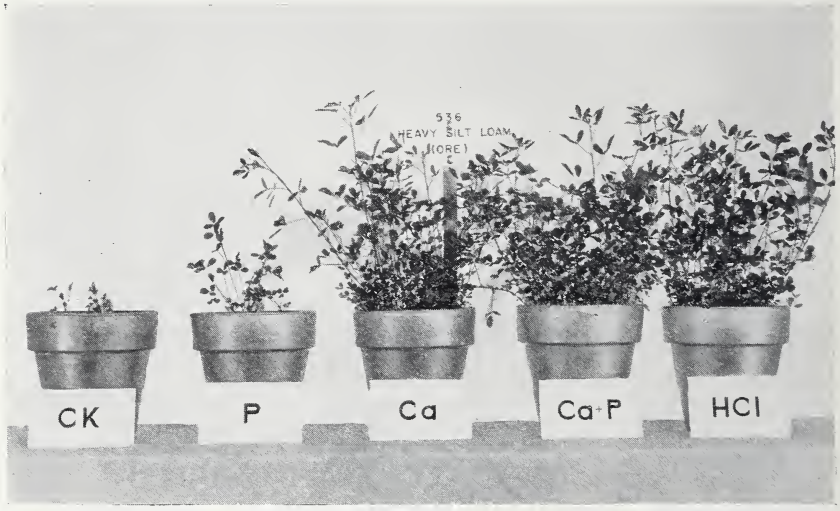

FIGURE 6.—The response of alfalfa to additions of phosphorus, calcium, calcium and phosphorus, and hydrochloric acid to an unproductive alkali soil. The pot at left (check) contains untreated soil. This is a typical alkali soil, relatively low in total salts but high in sodium. It has poor physical condition and very low permeability.

cause the root systems improve the physical condition of impermeable soils. Rice is an ideal crop for reclamation, since it can grow submerged and salts are being leached out at the same time that the crop is being grown. Large areas have been reclaimed by flooding and growing rice without any other treatment. It is particularly successful where the soil contains gypsum or the water contains a high proportion of calcium salts.

Irrigation and Soil-Water Relationships

The more extensive use of water for irrigation in the Western States requires careful consideration of efficient methods of irrigation, quality of water, and soil-water relationships. When the irrigation water contains moderate amounts of salt, sufficient water must be applied to prevent salt accumulation in the soil and to leach out excess salts in soils where they have already accumulated. Several studies have been made of quality of water and this information is now available.

An experiment to determine the amount of leaching necessary to prevent salt accumulation has been in progress since 1943. Low and high salt waters containing low, intermediate, and high proportions of sodium have been used to irrigate soils in tanks (lysimeters) provided with drains from which the leachate can be collected for measurement and analysis (fig. 7).

FIGURE 7.—*A*, Alfalfa, growing in "lysimeters," is watered with typical irrigation waters. *B*, Samples of the water from the bottom of each lysimeter, obtained through connecting drainage lines, can be analyzed to determine any change in salt content during the irrigation.

The movement of salt in the soil is closely associated with water movement, and for this reason considerable attention has been paid to the flow and distribution of water in soils. Several instruments have been designed to determine soil-moisture relationships more accurately. One apparatus used to extract water from the soil under pressure has been patented and "dedicated to the free use of the people in the territory of the United States."

The availability of moisture to plants is a vital consideration in irrigation agriculture. A salt-free silt loam soil may contain 30 percent of water shortly after irrigation. When the moisture content is reduced to 15 percent, plants may wilt because they can no longer withdraw sufficient quantities of water from the soil. The amount of moisture that the soil will hold against the force of gravity is termed the "field capacity," and in general it varies with the fineness of the particles making up the soil. The moisture content known as the "wilting percentage" is the point at which plant roots are no longer able to absorb moisture from the soil at a sufficient rate to keep the plant from wilting. The water in the soil, including all dissolved materials, is often called the "soil solution."

In a soil containing little salt, plants will wilt at certain low moisture contents (wilting percentages) because the water is held by the soil with such great force that the plant cannot obtain enough water to live. The tensiometer, an instrument for measuring the security with which water is held by the soil, has been improved in design and adopted for use at the laboratory. It may be used to indicate whether the moisture content is increasing or decreasing, and the direction of movement of soil moisture. Although the tensiometer will not measure the water-holding force of the soil down to the wilting range, it has definite usefulness for studying and controlling moisture movement in connection with irrigation.

Plants and Plant-Soil-Water Relationships

In saline soils, the presence of appreciable quantities of soluble salts makes it more difficult for plants to obtain water, owing to the increase in the osmotic pressure of the soil solution.

Osmotic pressure can be explained as follows: If a salt solution is placed inside a bladder or membrane which is permeable to water but not to salt, and the bladder is placed in a pail of water, there is a tendency for the salt concentration to be equalized inside and outside the bladder. Because salt cannot pass outwards through the bladder but water can pass in either direction, the end result is increased water inside the bladder. Water can be prevented from accumulating in the bladder if pressure is applied on the solution inside. Such pressure, called osmotic pressure, measures the water-absorbing force. The greater the concentration of salt within the bladder or membrane, the greater is the osmotic pressure [2]—that is, the greater the pressure required to keep water from coming through the membrane. When a salt solution instead of water is placed in the pail, there is less tendency for water to pass through the bladder, and if the composition and concentration of salt on each side of the bladder were equal, the rates of passage of water through the membrane from both sides would be equal.

[2] Osmotic pressure is usually expressed in units called "atmospheres." One atmosphere equals 14.7 pounds pressure per square inch.

The condition described above might exist when a plant is growing in a saline soil. In such a case, the greater the concentration of salts in the soil solution, the more difficult it would be for the plant to obtain water. As the soil dries and the moisture content is reduced, the salt concentration and the osmotic pressure of the soil solution both increase and the intake of water by the plant is reduced.

At or near the wilting percentage the salt concentration will be the greatest that the plant is subject to in that soil. In order to get an idea of what salt concentrations are involved, the pressure membrane apparatus is used to obtain samples of the soil solution from soils with moisture contents near the wilting percentage. Analyses of small amounts of solution so obtained from a number of representative western soils showed a wide range in salt concentration. The nonsaline or slightly saline soils had low osmotic pressures, while strongly saline soils had solutions with osmotic pressures as high as 40 atmospheres. In these latter soils plant growth was very poor or nonexistent, even though most of the time the moisture content was considerably above the wilting percentage. Salt contents corresponding to these osmotic pressures ranged from about two-tenths of 1 percent to 7 percent, or 2,000 to 70,000 parts of salt per million parts of soil solution.

Some of the relationships between plants and saline soil solutions have been investigated in water and sand culture experiments. This method makes it possible to run carefully controlled experiments to determine the water relations of plants grown in salty solutions and the effects of specific salts on plant growth. It was found that growth of plants was reduced approximately in proportion to the increase in osmotic pressure of the nutrient solution, no matter which of the common salts was employed. Hence the conclusion was drawn that growth was reduced mainly because of lack of water to the plant. Just as a man on the ocean may die of thirst, these plants were unable to get their full requirement of water for good growth.

Water Intake by Plants, Measured Directly, Is Lower at High Salt Concentrations

By means of a simple apparatus developed at the Salinity Laboratory water intake can be measured for a definite area of a single plant root. In experiments with corn roots the rate of water intake was determined for control plants and for similar plants in solutions of increasing salt concentration. For example, when the roots were placed in salt solutions with an osmotic pressure of 4.5 atmospheres the rate of entry of water was reduced 88 percent as compared with the intake in solutions of one-half atmosphere. In sugar solutions of 6.8 atmospheres, there was no water intake by young corn roots. Concentrations of salt as great as these are found in saline soil solutions, and the fact that different salts, by actual measurement, reduced water intake at these osmotic pressures helps to explain why plants obtain water less readily in salty soils. This and other studies at the laboratory indicate that the addition of salt to the soil solution has an effect in reducing the absorption of soil moisture by plants. This effect is separate from and in addition to the increase in the force with which the soil holds water as it dries out.

The Influence of Salts and Reduced Water Supply on Growth and Composition of Plants

The effect of salts and reduced water supply on yield has been studied for a number of crops. In an experiment with alfalfa, it was found that an increase of 4 atmospheres osmotic pressure reduced the yield more than 50 percent (fig. 8). Reduction in vegetative growth and yields has been observed for beans, flax, tomatoes, cotton, peaches, grapefruit, wheat, and a number of grasses. Studies made at the Salinity Laboratory showed that at high concentrations of salt (3.5 to 4.5 atmospheres osmotic pressure) relative yields of flaxseed were reduced 25 to 60 percent, and that sodium

FIGURE 8.—Yields of alfalfa grown at 0.5, 2.5, 3.5, and 4.5 atmospheres of osmotic pressure. The figures on the containers indicate the increase in osmotic pressure produced by adding sodium chloride to the nutrient solution. BN (left) is the control culture, grown in the base nutrient solution with nothing added; osmotic pressure, 0.5 atmosphere.

sulfate was more injurious than chloride salts at equal osmotic concentrations.

Experiments with beans illustrate the effects of high salt concentrations, kind of salt, and soil-moisture content on vegetative growth and yield. Bean plants were grown in the greenhouse in water cultures containing an adequate supply of nutrients to which were added varying amounts of sodium sulfate, sodium chloride, calcium chloride, magnesium chloride, and magnesium sulfate (fig. 9). The results indicated that in addition to the depression of growth resulting from osmotic pressure there may be injury due to the poisonous effect of a certain element. In this case, magnesium salts were more toxic than the salts of sodium or calcium.

Beans have also been grown in soils varying in salt content and moisture percentage. The effect of increasing salinity in the soil is similar to that of increasing the salt content of water cultures, as shown in figure 10. As the soil moisture is depleted after irrigating, the rate of growth of the plants decreases even in nonsaline soil. A study of figures 9 and 10 shows that increasing salt concentration decreased growth of bean plants and yield of

FIGURE 9.—Dwarf Red Kidney bean plants grown in solution culture show the influence of different concentrations of various salts on their growth, compared at equal osmotic pressures. Figures on the jars indicate the osmotic pressure expressed in atmospheres. The osmotic pressure of the base nutrient solution (B. N.) was 0.5 atmosphere. Reading from top to bottom the salts added were: Sodium sulfate, sodium chloride (common salt), calcium chloride, magnesium chloride, and magnesium sulfate.

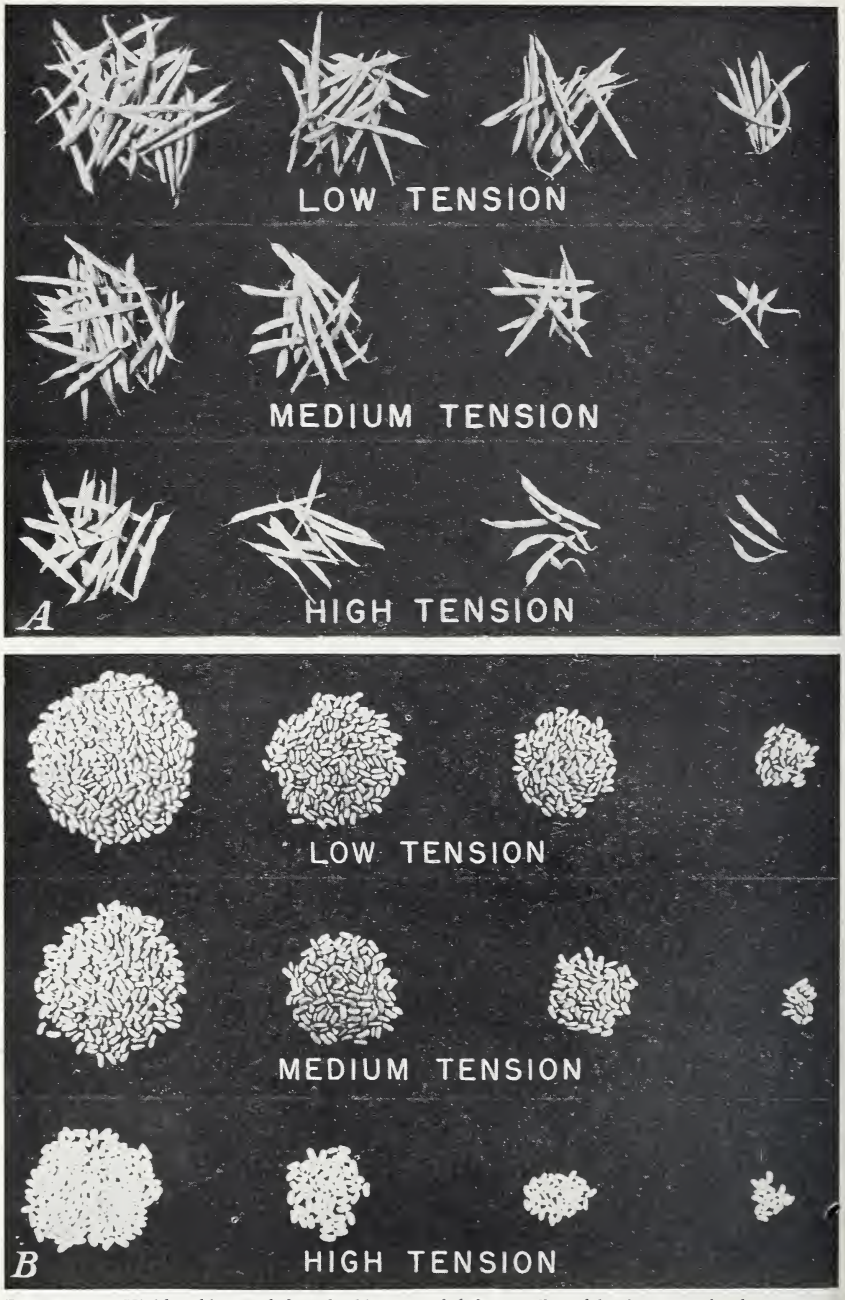

FIGURE 10.—Yields of beans (*A*) and of bean seed (*B*) are affected by increases in the amounts of sodium chloride (common salt) in the soil and by moisture stress. From left to right in each picture: No added salt; sodium chloride (dry-soil basis) 0.1 percent, 0.2 percent, and 0.4 percent. Low-tension series: soil never allowed to dry. High-tension series: soil-moisture percentage approached the wilting stage before each irrigation. Medium-tension series: intermediate in moisture stress.

beans, and that a deficiency of water without excessive salinity also decreased plant growth.

It has long been known that, on a weight basis, chloride salts are more toxic than sulfate salts. When the two salts are compared on the basis of equal osmotic pressures of the nutrient solutions, they usually behave about the same. However, experiments at the Salinity Laboratory showed that the growth of some crops, such as peaches (fig. 11) and beans, was reduced more by chloride than by sulfate salts. Flax, guayule, and some grasses, on the other hand, were affected more severely by sulfate salts. This indicates that there are definite plant differences with respect to tolerance

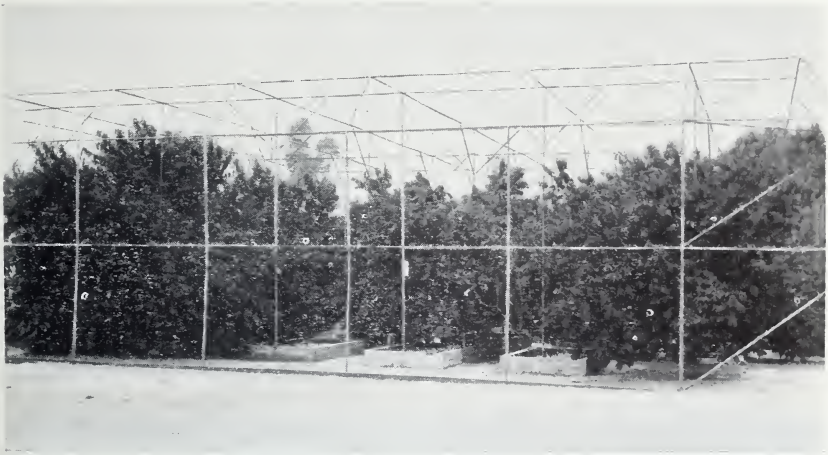

FIGURE 11.—General view of Elberta peach trees in large sand tanks, showing the condition of the trees in September 1944. The trees are protected from birds by a screened enclosure. Although all are the same age (about 5 years old) some are considerably smaller than others, reflecting the reactions to the six different salt treatments used. Where the more concentrated salt solutions were used, some trees did not survive and were removed.

to specific salts. Although availability of water is the principal consideration in saline soils, the kind of salt present cannot be ignored.

Diagnosis of Salt Injury or Toxicity

In general, plants show few characteristic symptoms of salt injury unless the concentration of salt is very high. The outstanding growth response to saline soil solutions is a reduction in the size of the plant and in its yield. Unless plants grown under nonsaline conditions are available for comparison, the dwarfing effect of salty soils may not be apparent.

Particular attention has been given to characteristic plant symptoms that might be of diagnostic value under field conditions. A common one is the burning, or drying out and browning, of leaves, which in many cases is associated with high concentrations of chloride in leaf tissues. The degree of burning appears to depend on the amount of chloride accumulated and the specific sensitivity of the plant. It usually starts as a tip burn and may extend along the leaf margins until the major portion of the leaf is involved. In severe cases there may be dropping of leaves and partial defoliation of the plant. This symptom has been observed in studies of peaches, barley,

milo, beans, and grapefruit. Dieback of young twigs is another symptom associated with high chloride and sulfate accumulations in peaches and grapefruit.

In some instances the leaves may become chlorotic, but this symptom is not specific for salt injury and is probably associated with a disturbance of the nutrition of the plant. The occurrence of chlorosis in the Western States is a serious and complex problem and the causes of it are not fully understood. The Salinity Laboratory hopes to undertake a study of chlorosis after completing some of the current research projects.

The Relation of Climatic Factors and Salinity

Some western farmers believe that saline soil conditions are more detrimental to crop growth in hot weather than during cooler seasons of the year. Others have noted that damage to crops due to salt is more serious in the hot interior valleys than in regions where the climate is more moderate. Information on this question is important to the development of management practices and the proper selection of crops to meet salinity conditions at different seasons and under different climatic conditions.

The Salinity Laboratory conducted a series of experiments to determine the tolerance of crop plants to the salts commonly found in irrigation waters and soils and to what extent climate modifies these effects. Identical experiments were set up in a cool coastal climate, a hot dry climate, and one intermediate between the two. The studies extended over a 3-year period. Sugar beets, table beets, cotton, milo maize, alfalfa, tomatoes, cowpeas, carrots, squash, onions, and beans were tested. Their relative salt tolerance

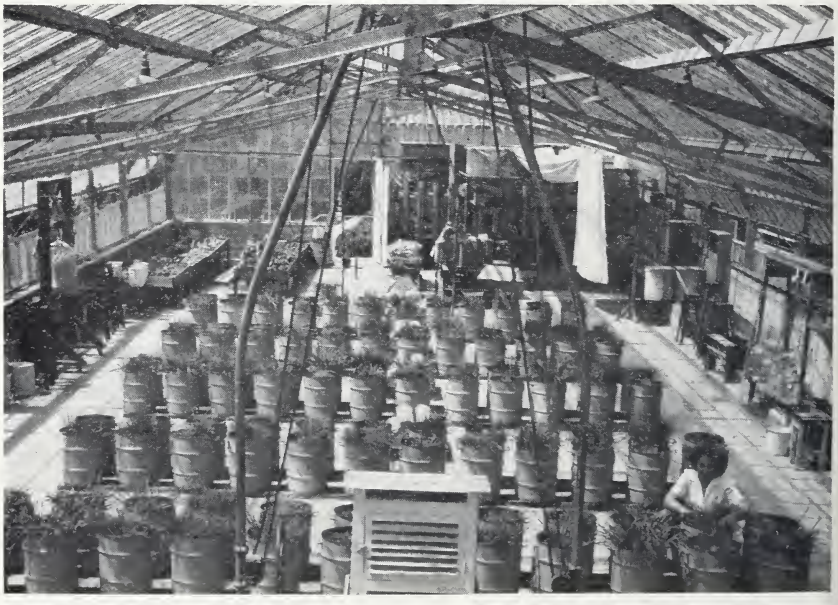

FIGURE 12.—General view of one of the greenhouses, showing how different grasses are grown in drums containing nonsaline and saline soils. The rate of growth of these grasses in the different soils and the rate of moisture loss by transpiration can be measured under carefully controlled conditions.

at Riverside, Calif., is indicated in descending order in table 1. For most crops the injury due to salt was greater in warm than cool climates, but all crops did not behave alike in their reaction to salt and climate. Cotton in the cool climate actually produced higher yields with some added salt than without it, and did better under normal nutrient conditions in the warmer climate of Riverside than in the cool coastal climate. Cowpeas were little influenced by differences in climate. More recent studies at Riverside with forage and pasture grasses have shown that the salt tolerance of some species is seriously affected by high soil temperatures, while others do very well under such conditions (fig. 12). Further studies are in progress to determine the relation of climate and salt tolerance, and plans are being made to set up identical cooperative experiments with some of the State experiment stations to compare results in different climates.

TABLE 1.—*The relative tolerance of some western crop plants to salt constituents in the soil solution*

Strong tolerance	Good tolerance [1]	Medium tolerance [1]	Weak tolerance
Sugar beets.	Barley (hay crop).	Onions.	Beans, wax.
Garden beets.	Tomatoes.	Squash.	Beans, navy.
Milo.	Alfalfa.	Carrots.	Field peas.
Bermuda grass.	Cotton.	Asparagus.	Horsebean.
Rhodes grass.	Sorgo.	Cowpeas.	Red clover.
Alkali sacaton grass.	Kale.	Rice.	Vetch.
Rescue grass.	Rape.	Rye (grain crop).	Proso.
	Perennial ryegrass.	Barley (grain crop).	Oats (grain crop).
	Wild ryegrass.	Wheat.	Emmer (grain crop)
	Italian ryegrass.	Oats (hay crop).	Peaches, Elberta on Lovell rootstock.
	Crested wheatgrass.	Grain sorghums.	
	Slender wheatgrass.	Foxtail millet.	
	Mountain bromegrass.	Flax.	
	Tall fescue.	Guayule.	
	Reed canary grass.	Sunflower.	
	Sudan grass.	Ladino clover.	
	Blue grama grass.	Strawberry clover.	
		Sweet clover.	
		Smooth bromegrass.	
		Meadow fescue.	
		Orchard grass.	
		Dallis grass.	
		Tall oatgrass.	

[1] A few crop plants listed in the medium and good groups do not die in strong salt concentrations, but they fail to make appreciable growth.

Salt Tolerance of Plants and Variations Within a Given Species

The farmer is usually a keen observer, and he early noticed that some crops were far more salt-tolerant than others. Sugar beets, alfalfa, and cotton have long been considered among the most salt-tolerant of the commonly grown crops. As more experimental data are obtained, the laboratory is classifying the western crops on the basis of their salt tolerance. The provisional list given in table 1 is based in part on less recent work done elsewhere. It is expected that some changes in classification will be necessary as more information regarding salt tolerance is obtained.

It was thought that because there is a wide range of salt tolerance between different kinds of plants, there may also be considerable difference in salt tolerance between strains or selections of a single crop. Preliminary evidence along this line was obtained with tomatoes and an exploratory test was made with cotton. A more recent test with 16 cotton varieties or selections, repeated for the third season, gives clear evidence that such differences do exist. Some selections of the California Acala variety of cotton, the New Mexico Acala, and the S X P variety grown in Arizona were found to be especially salt-tolerant. Tests are in progress to compare fiber quality of cotton from these tests. To date, salt does not appear to affect quality or neppiness in cotton, although the kind of salt affects yields.

Similar tests are now in progress with several varieties of alfalfa, including two obtained from North Africa, in order to find, if possible, one that will be more salt-tolerant than the varieties now grown in the West. As a result of preliminary trials, six varieties have been selected for testing: California Common, Arizona Chilean, Ranger, Hegazi, Demnat, and Tunisia. These are being grown in the large sand tanks to permit ample room for root development during several seasons. The study will be continued long enough to determine how each variety responds to saline solutions under successive croppings and seasonal changes.

SOME APPLICATIONS OF RESEARCH TO PROBLEMS IN THE FIELD

One of the major objectives of the Salinity Laboratory is to make practical applications of the results of its research program. These include improved methods of analysis, better farm-management practices, procedures for use in drainage and irrigation districts, crop recommendations on the basis of salt-tolerance studies, and technical assistance in reclamation work.

At present, the agriculture of the Coachella Valley in California is entirely dependent on a pumped water supply. Within a short time, water from the Colorado River will be available for irrigation in the valley. This change may increase the drainage problem, and the Coachella Valley County Water District has asked public agencies to assist in developing a satisfactory drainage program. The Salinity Laboratory in collaboration with the California Agricultural Experiment Station and the water district is actively engaged in field tests to determine the effectiveness of establishing drainage wells equipped with pumping facilities to control the water table and remove excess salts. Ground-water observation wells developed at the laboratory are being used to determine the water-table positions. The results obtained in this project will provide information that can be applied to drainage problems in other areas in the West.

The Salinity Laboratory is participating actively with the Utah Agricultural Experiment Station and four Millard County drainage districts in a cooperative drainage and reclamation study at Delta, Utah. This area of about 50,000 acres of irrigated land is not adequately drained, although several million dollars have been spent for drainage works. Other areas where the Salinity Laboratory has been requested to give technical advice and assistance on irrigation, drainage, and water-spreading problems are the Moapa Valley, Nev., including the Moapa Indian Reservation (at the request of the U. S. Indian Service), the Grand Junction area in western Colorado, Kern County in the Central Valley of California, the Owyhee

project in Oregon, the Yakima Valley of Washington, and the Yuma Mesa project in Arizona.

Methods and instruments developed at the Salinity Laboratory are being used in these field investigations, and the facilities of the laboratory and the advice of the professional staff have been made available as far as manpower and budget permit.

At the request of the Guayule Research Project, special studies were carried on during the war to obtain information on the salt tolerance of guayule and the effect of soil salinity and methods of irrigation on growth and rubber production of this plant. The results were transmitted to the field workers and used in the selection of suitable sites for guayule plantings.

Salt-tolerance trials on cotton have been carried on in close cooperation with the U. S. Cotton Field Station at Shafter, Calif. New and improved varieties developed there are being tested at the laboratory prior to their release, and the information obtained should materially assist in the cotton-breeding program for strains adapted to saline conditions in the Southwest. Further information on the salt tolerance of many western crops is being gathered each year. These data are transmitted to the State experiment stations or are published so that they may serve as a guide in selecting suitable crops for saline areas.

A BRIEF RÉSUMÉ OF THE RESEARCH PROGRAM AND WHAT HAS BEEN ACCOMPLISHED

The United States Regional Salinity Laboratory is endeavoring to promote effective and efficient crop production on 20 million acres of irrigated land, of which about half has had its productivity impaired or threatened by the accumulation of injurious concentrations of salts. The research program of the laboratory includes development of improved methods of leaching salts from soils; increasing soil permeability and drainage; determination of the salt tolerance of important crops, and selection of salt-tolerant strains of these crops; and development of cultural practices that will reduce salt accumulations or their effects on plants.

Among the accomplishments of the Salinity Laboratory are these findings:

1. A new type of ground-water observation well, known as a ground-water piezometer, has been developed for determining ground-water pressures at various depths. This has simplified the determination of position of the water table and the direction of ground-water movement, essential in determining the need for and proper methods of removing excess ground water by artificial drainage. These new methods have been applied in saline areas of one important irrigation district.

2. Work on water-spreading problems has resulted in the development of satisfactory methods for obtaining cores of undisturbed soil and for conducting permeability tests. A better interpretation of soil permeability characteristics is now possible. As a result of this study we now know that the sealing of the soil under continuous submergence occurs chiefly near the surface. We also know how best to overcome this sealing and improve the efficiency of water-spreading operations.

3. Along with the work of other agencies, the Salinity Laboratory has demonstrated that fertilizers containing sodium salts may cause soil to run together and lower permeability, especially if the fertilizer is supplied in concentrated bands or in concentrated solution. This explains why some

growers have been troubled by soils absorbing water less readily after the use of fertilizers containing sodium salts.

4. New methods for measuring and expressing the storage and availability of soil moisture for plant use have been developed at the laboratory. Although these techniques and devices were originally developed for research tests, they are now being employed in soil survey and classification work and for irrigation control by commercial growers.

5. Reductions in plant growth due to salinity are roughly proportional to the increase in total salt concentration in the soil solution. In certain tests, soils were unable to support plant growth when the concentration of salts in the soil solution exceeded approximately 10,000 parts per million. At any given concentration each of the commonly occurring salts had about the same effect, but special toxic effects of some salts have been noted for certain plants.

6. The entry of water into roots has been measured quantitatively. It has been shown that increasing the osmotic pressure of the solution by the addition of salts results in a decrease in the intake of water by the root. This confirms other studies on the effect of additions of salt to the soil solution and helps to explain reductions in plant growth due to salinity.

7. Flax has only a moderate salt tolerance, and yields will be low when it is grown on soils with high salt content. Guayule is particularly sensitive to soluble magnesium and cannot be grown satisfactorily on soils containing more than moderate amounts of common salt.

8. Garden beets, milo sorghum, sugar beets, alfalfa, and cotton are relatively tolerant to salt, whereas peaches, beans, and onions are intolerant and are killed or injured at fairly low concentrations.

9. Studies of the salt tolerance of different strains and hybrids of cotton show the feasibility of breeding crops for increased salt tolerance.

RESEARCH PROGRAM FOR THE NEAR FUTURE

The preceding sections have discussed the salt problem and its vital importance in western agriculture. The major activities of the Salinity Laboratory and phases of its research program have been described. The problems are complex and many questions remain to be investigated. The laboratory will be able to contribute increasingly to the solution of salt problems encountered by various agencies in the field as it accumulates further information on this general subject and develops improved methods and procedures for diagnosing and ameliorating them.

The current research program includes the following studies:

1. **Chemical and physical factors affecting soil permeability.**—Good drainage is the heart of the problem of maintaining production on irrigated lands, and good soil permeability is the key to the drainage problem.

2. **Selection and improvement of drainage methods.**—By an intelligent study of local conditions it should be possible to plan drainage systems that function well and are economical. In many areas drainage by pumping is unknown, but with increasing availability of electric power at low cost, pumping may become more economical than drainage by open and tile drains. Much of this work will be done in cooperation with drainage districts and State and Federal agencies.

3. **Reclamation of alkali lands.**—The general theory of reclamation is known, and much experimental information is available on the subject, but

a great deal remains to be learned, especially on the quantitative side, so that more specific instructions can be given to the farmer. Alternative soil amendments such as sulfur, sulfuric acid, and aluminum sulfate may become more feasible, and they merit more study.

4. **Survey and diagnosis of saline and alkali areas.**—There is an increasing need for better and more uniform methods of diagnosing saline and alkali soil conditions before reclamation programs are initiated. The Salinity Laboratory is studying techniques that survey personnel can use in the field in order to better appraise salinity conditions and the possibility of correcting them.

5. **Plant tolerance to saline soils.**—This subject has only been opened and appears to justify continued study by the plant scientists. It is still not known why decreased water supply decreases growth, and there is little information regarding the chemical changes that go on within the plant as a result of accumulation of salt in plant tissues. There are great differences in the salt tolerance of crops and more study is needed so that they can be more accurately classified in this respect and the farmer advised as to those most likely to succeed. The effect of salt on quality of forage plants and edible plant products also merits attention. It is expected that there will be increased participation by the State experiment stations in this work so that the effect of climate on salt tolerance can be determined.

6. **Germination and early growth.**—The early stages of plant growth are the most critical, but often the crop can be carried past this period by special measures. Information is needed on the effect of soil conditions, salt concentration, and alkali on germination. Improved field methods are needed to overcome harmful conditions at this stage.

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